HAZARD METRIC UNIFICATION

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Motivation

- **To provide a recommendation for the best turbulence hazard metric given its intended function**

OUTLINE

- Definition of Turbulence
- Aircraft Response to Turbulence
- Hazard Metric
  - RMS Normal Load
  - Eddy Dissipation Rate
  - Aircraft Centric or Atmospheric Centric
- Advantages and Disadvantages of Each Metric
- Summary and Recommendations

Definition: Atmospheric Turbulence

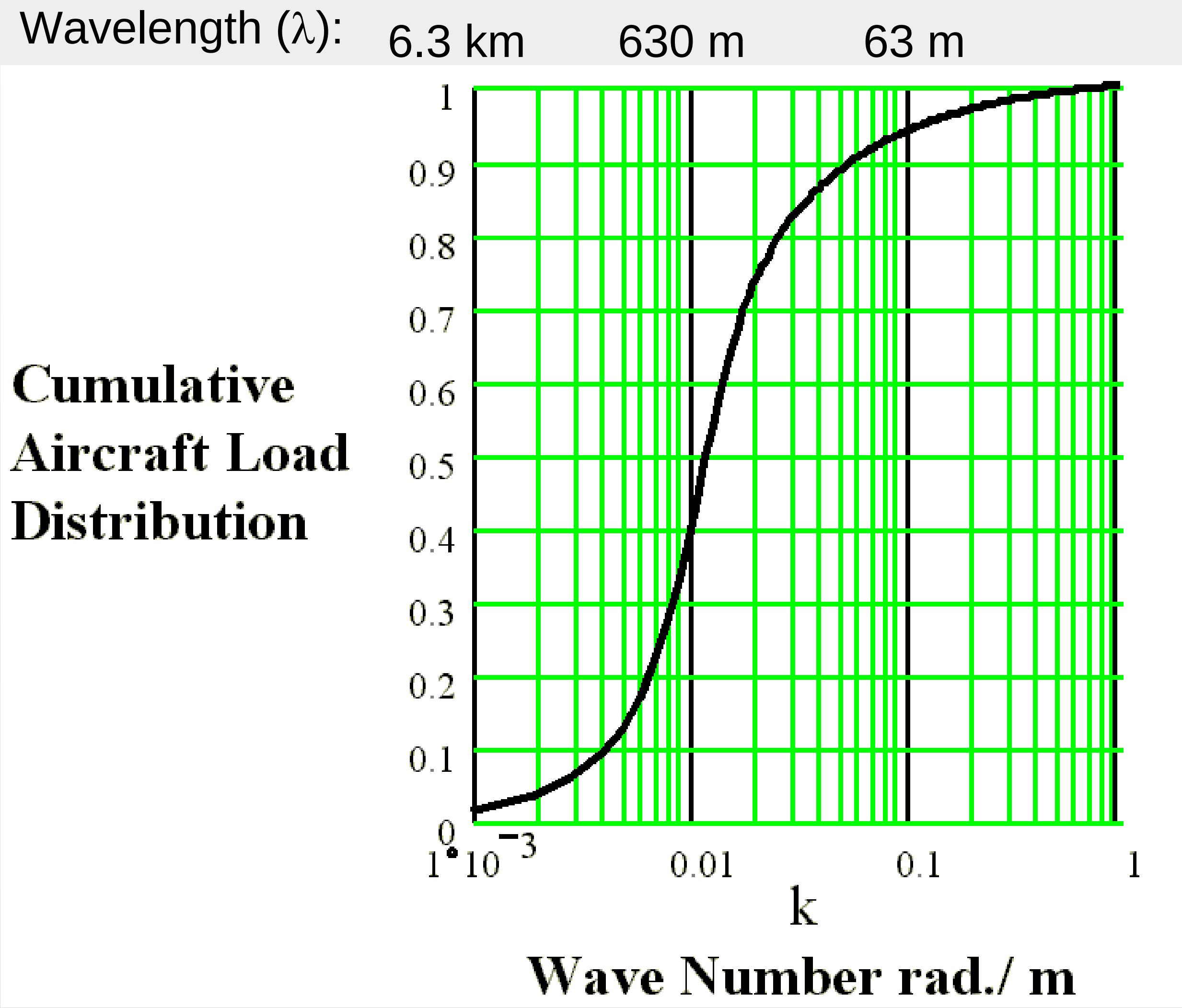
- **According to Stull, airflow or wind, can be divided into three broad categories:**
  - **Mean wind**
  - **Waves**
  - **Turbulence**
- **Turbulence in the atmosphere is often defined as the deviation of fluid velocity from some mean, where the mean is determined from either a fixed time or space interval**
- **The intensity of the atmospheric turbulence can be characterized by many parameters (i.e., turbulence kinetic energy, velocity variance, turbulence eddy dissipation rate, turbulence integral length scale, etc)**

Aircraft Response To Turbulence

- **Aircraft flying through such a perturbed flow field will respond depending upon the fluid scale of motion, aircraft type, altitude, air speed, and weight.**
- **Different aircraft may respond dissimilarly to the same turbulence field.**
- **Aircraft only respond to a specific range of turbulence scales. Small (λ<40*m*) and very large scales of motion (λ>4000*m*) impart negligible accelerations on the aircraft.**

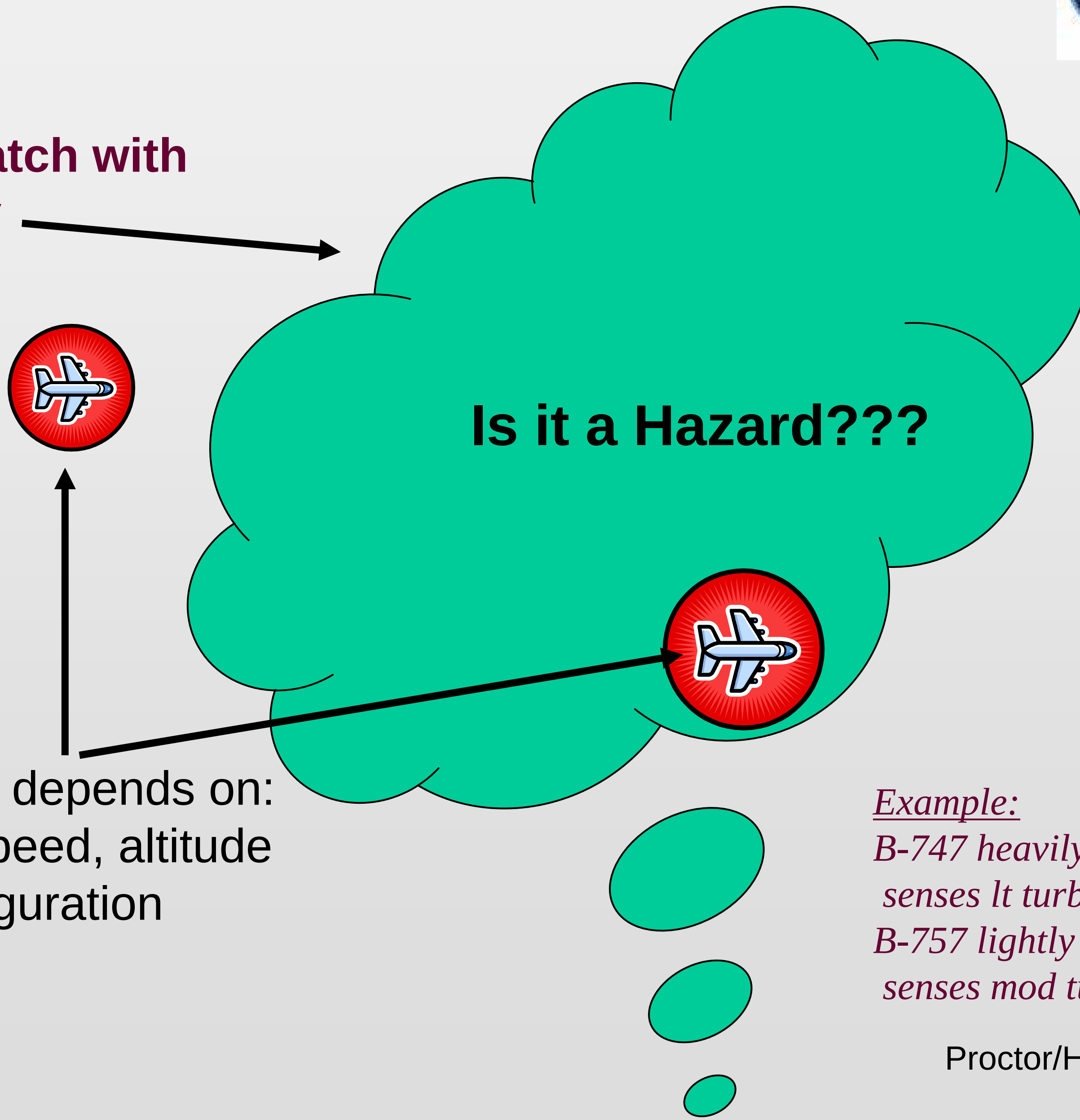
Aircraft Response

Cumulative distribution of normalized aircraft loads as a function of wave number. Aircraft calculation based on B-757-200 frequency domain model. Assumes von Karman turbulence spectrum with an outer scale of 300 m and σ_w=1 m/s. (provided by Roland Bowles)



Idealized Encounter with Turbulence

Turbulence patch with fixed intensity



Aircraft response depends on: aircraft weight, speed, altitude and aircraft configuration

<u>Example:</u>
B-747 heavily loaded senses lt turbulence
B-757 lightly loaded senses mod turbulence

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Hazard Metric

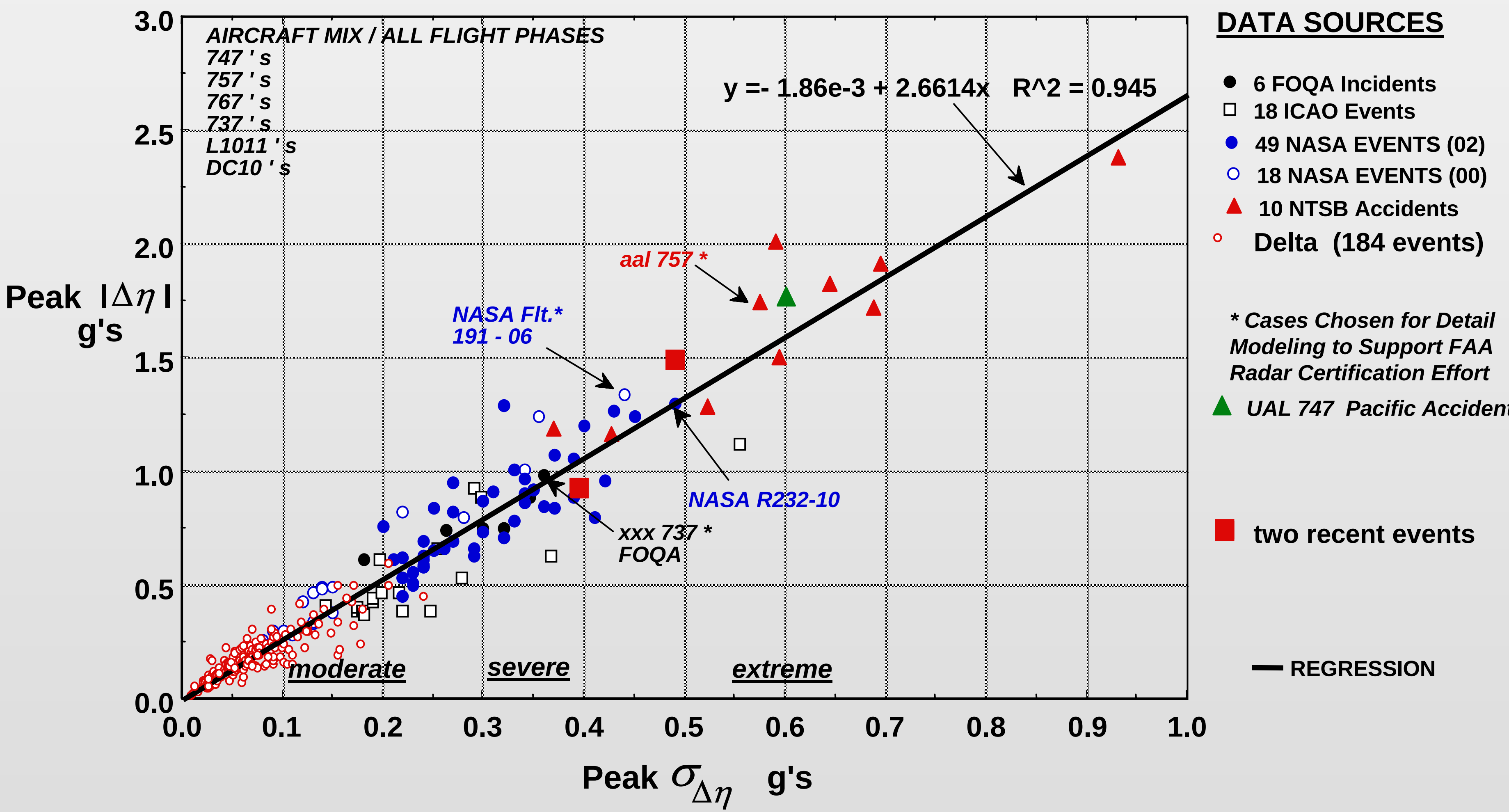
- Issues of Debate
  - Aircraft Centric or
  - Atmospheric Centric
- Metrics
  - Root Mean Square (RMS) of Aircraft Normal Load
  - Eddy Dissipation Rate (EDR)
- Choice depends on if one wants to characterize the atmospheric turbulence conditions, or does one wish to characterize the turbulence effect on the aircraft?

RMS Normal Load

- The root mean square of the aircraft's normal acceleration represents the "turbulence" response of an aircraft to turbulent air motions
  - statistically quantifies the sharp bumps and accelerations that passengers feel when flying in an aircraft
  - simple to calculate from direct measurements available from the aircraft's accelerometers
  - assumes a 5 second window

Correlation of Peak Load With Peak RMS Load
(5 sec. window)

Based on Measurements for 291Turbulence Encounter Cases



ESTIMATED FROM RADAR OBSERVABLES FOR TPAWS CONCEPT

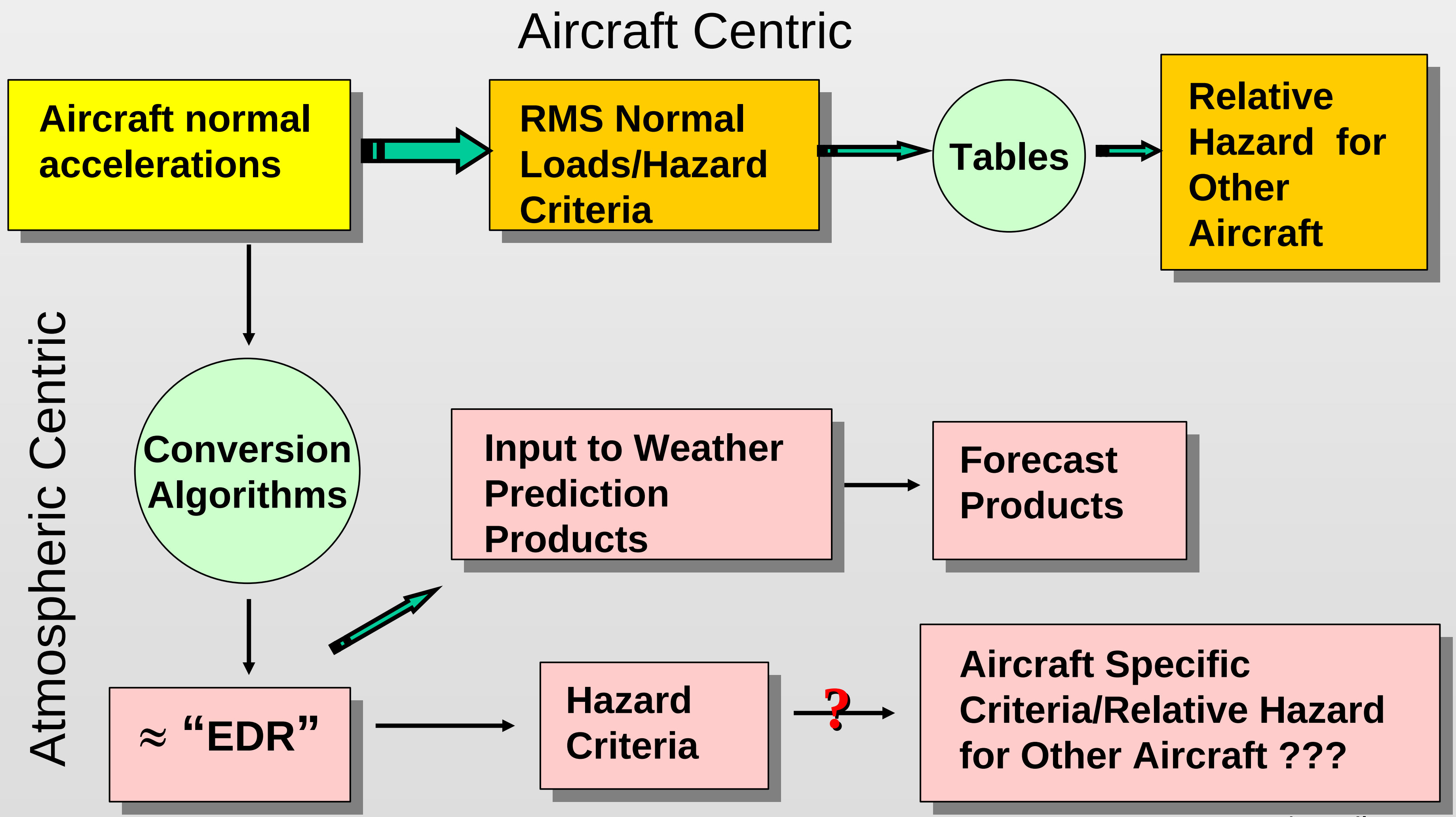
Bowles

The Eddy Dissipation Rate (EDR)

- EDR attempts to quantitatively describe the rate at which turbulence energy is transferred from large to small scales of turbulence where it is then damped by molecular viscosity and irreversibly converted into heat

- EDR is not directly measurable, but must be inferred
  - more than one method for deriving EDR, each of which may provide very different values for an identical turbulence field
  - in the calculation of EDR, assumptions are often invoked which include homogeneity, isotropy, and the existence of an inertial subrange of turbulence scales

Aircraft Centric or Atmospheric Centric?



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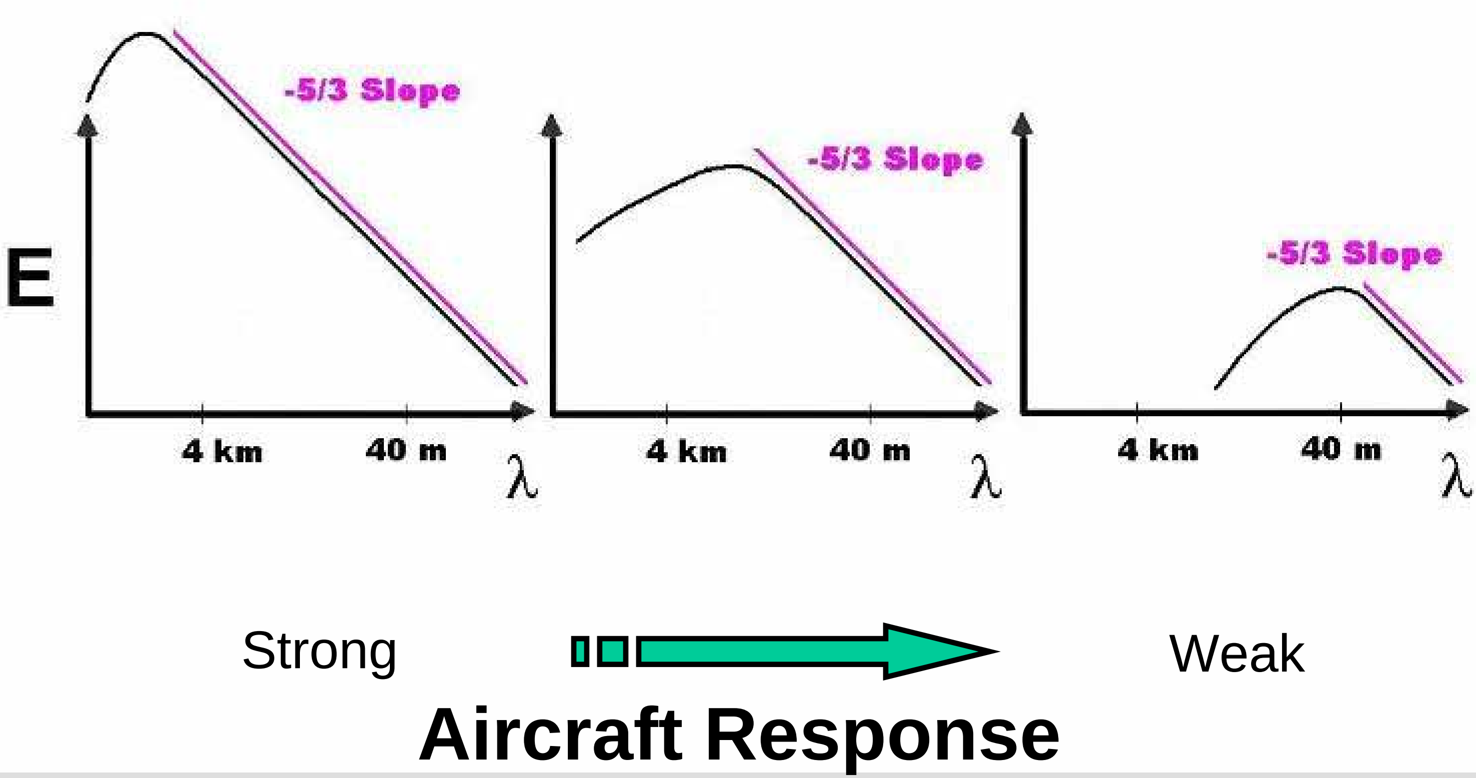
Advantages of EDR

- EDR can be an acceptable parameter in quantifying the properties of turbulent fluid flow under certain validated assumptions
- EDR can provide an estimate for the intensity of atmospheric turbulence
- Aircraft reports of EDR can be used to initiate weather forecast turbulence products
- Knowing the EDR of the atmosphere could be useful in other applications unrelated to flight turbulence (i.e. weather forecasting, wake separation, and air pollution dispersion)

Can aircraft response be determined from EDR?

Each of these three spectra have same EDR. However, they have different turbulence outer length scales



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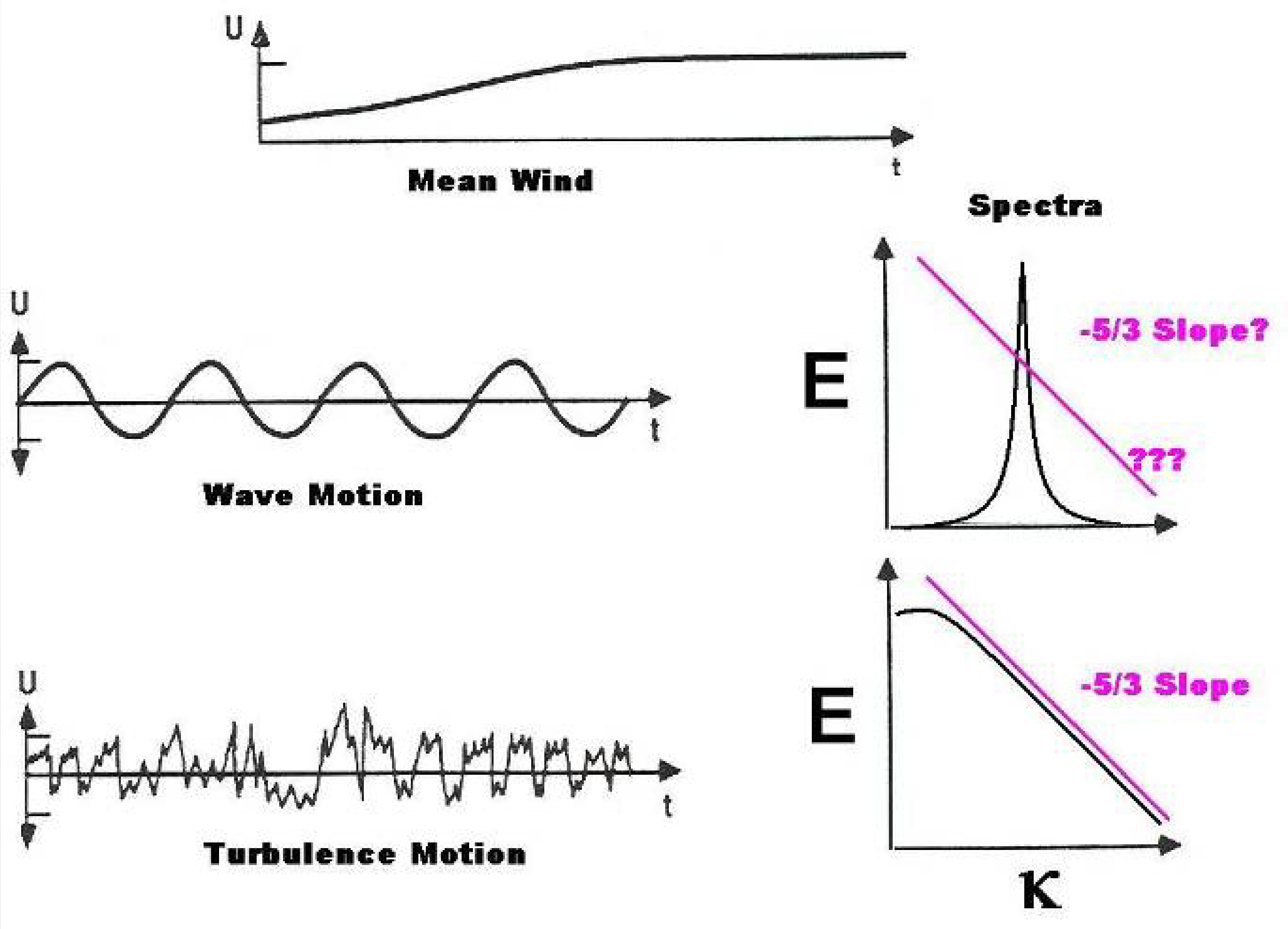
Types of Flow



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Disadvantages of using EDR

- EDR cannot be directly calculated or measured and must be inferred.
- There is no standard method for estimating EDR.
- How do you verify?
- Certain assumptions are required (isotropy, homogeneity, steady state turbulence) for the calculation of EDR to be theoretically valid. Furthermore, knowledge of the turbulence outer scale is critical for estimating EDR. (i.e. data must resolve the inertial subrange).
- A large sample of data is required to calculate EDR. Many have found ranges between 5 and 15 minutes is required for stable estimation. In this amount of time, some aircraft may have traveled up to 120 *nmiles*.
- Input data sampling frequency may dramatically affect the value of calculated EDR.
- Averaging time/space can significantly affect the value of calculated EDR, i.e. a large sample of data is necessary for providing a stable output of EDR.

Disadvantages of using EDR (continued)

- **Even if a turbulence patch is correctly characterized with an appropriate value for EDR, aircraft will respond dissimilarly as they penetrate this patch.**
  - **Therefore, a formulation is required to determine the relationship between EDR and aircraft turbulence response, i.e. light, moderate, or severe.**
  - **Although theory exists to convert an EDR estimate to a load estimate, there are several assumptions that are needed to be made; turbulence length scale, aircraft response function, limits of integration, and correction factors. Also required for conversion are parameters such as aircraft type, weight, altitude, and airspeed. The accuracy of this conversion has not yet been established.**

Advantages of RMS Normal Load

- The normal load metric is a direct calculation from measured aircraft response.
- Simple to implement because it is calculated from direct measurement.
- The normal load metric confidently quantifies the hazard imposed from the turbulence encounter upon the aircraft and its passengers.
- Transfer functions exist that allow for conversion of normal loads from one aircraft to another. For example, if two dissimilar aircraft encounter the same turbulence field, the normal load can be predicted for the following aircraft based on the normal load sensed by the preceding aircraft. This conversion is determined from known aircraft characteristics.
- Aircraft manufacturers, operators, and maintenance personnel understand the consequences of normal loads upon aircraft. Also, aircraft design limitation is usually expressed in terms of normal loads.
- The FAA has provided guidelines for reporting turbulence duration and intensity regarding the turbulence impact upon aircraft and passengers. These guidelines are consistent with the intended function of the normal load metric.
- An operational system based on the normal load metric has been demonstrated during the TPAWS program.

Disadvantages of RMS Normal Load

- Does not directly relate to conventional fluid metrics that characterize the intensity of the atmospheric turbulence (i.e., turbulence kinetic energy, turbulence eddy dissipation rate, turbulence integral length scale, etc)
  - However, this is usually not a concern to passenger and aircraft safety
- Not clear how this could be used to initialize NWS turbulence forecast products

Summary and Recommendations

- Based on our study to determine the most appropriate turbulence metric for application to flight safety, the normal load metric is the most preferred
  - metric is aircraft centric
  - relatively easy to deduce from standard flight systems
  - this metric is understood by the aircraft operators
  - operationally tested

Backup slides

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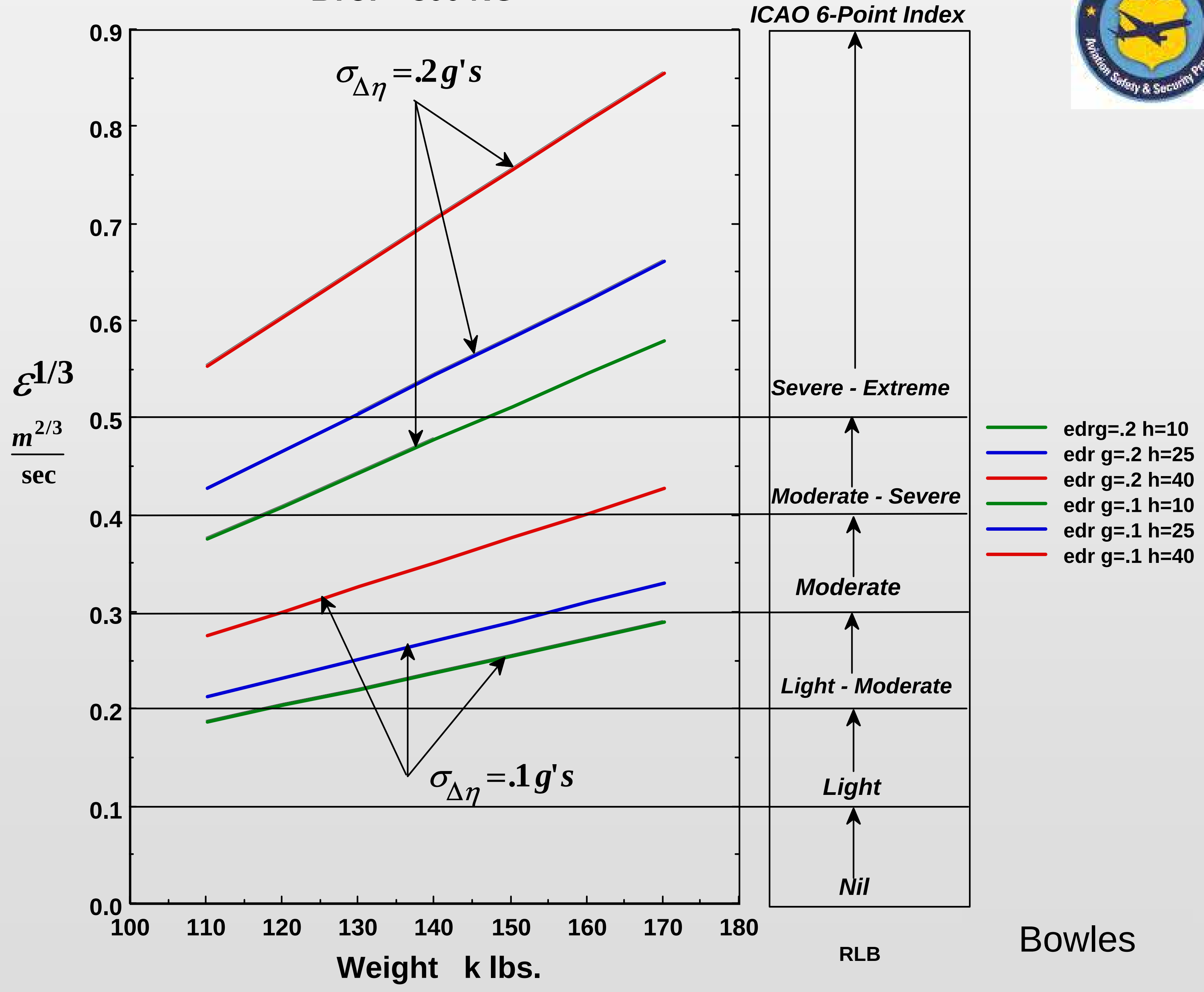
EDR REQUIRED TO ACHIEVE A GIVEN RMS g-LOAD
B737 - 800 NG



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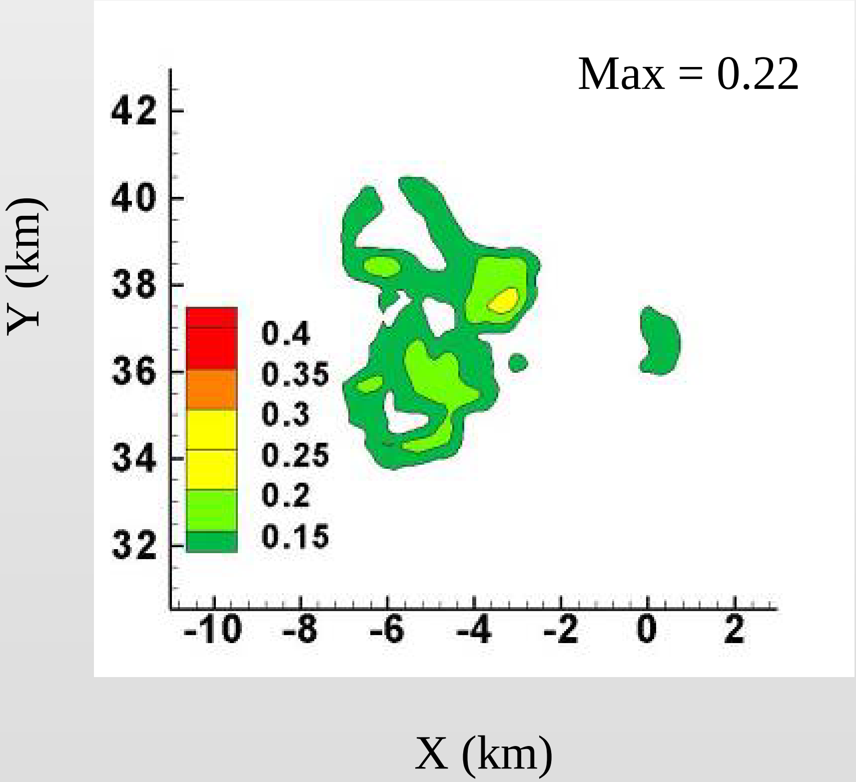
Horizontal Cross-Section of Simulated 191-6 Data Set. Sensitivity of Hazard to Aircraft Weight

RMS acceleration from $\hat{\sigma}_w$ at 10.3 km Elevation

B737-800 Trim at 170 klbs



B737-800 Trim at 100 klbs